ISSN 0040-6015, Thermal Engineering, 2012, Vol. 59, No. 3, pp. 236–241. © Pleiades Publishing, Inc., 2012.
Original Russian Text © M.A. Gotovskiy, M.I. Grinman, V.I. Fomin, V.K. Aref'ev, A.A. Grigor'ev, 2012, published in Teploenergetika.

Use of Combined Steam–Water and Organic Rankine Cycles for Achieving Better Efficiency of Gas Turbine Units and Internal Combustion Engines

M. A. Gotovskiy[a], M. I. Grinman[b], V. I. Fomin[b], V. K. Aref'ev[a], and A. A. Grigor'ev[b]

OAO NPO Central Boiler–Turbine Institute, ul. Politekhnicheskaya 24, St. Petersburg, 194021 Russia

OOO Komtek-Energoservis, pr. Bol'shoi Smolenskii 15, korp. 2, St. Petersburg, 192148 Russia

Abstract—Innovative concepts of recovering waste heat using low-boiling working fluids, due to which the the efficiency can be increased to 28–30%, are presented. If distributed generation of electricity or combined production of heat and electricity is implemented, the electrical efficiency can reach 58–60% and the fuel heat utilization factor, 90%.

DOI: 10.1134/S0040601512030032

Problems of achieving better energy efficiency and more efficient use of waste heat from energy-intense production processes are nowadays very pressing ones. Considerable experience with construction of waste heat recovery systems has been gained at Ormat, Siemens, Turboden, and other companies; however, real efficiencies of cycles that are implemented are limited to around 18%.

The problem of rationally using energy resources has attracted great attention of specialists since the middle of the past century, the time when rapid growth of industrial production generated the need to make it more energy efficient.

In many industries generating by-products and fuel (e.g., black leach and wood in the pulp and paper industry, synthesis gas in the petroleum refining industry, light gas mixtures obtained as a result of processing chemical substances, blasting gases in steel industries, etc.) it is possible to avoid losses of energy by utilizing it in one form or another. The problems of losses in systems using renewable sources of energy (solar, geothermal, and wind energy) for generating electricity are usually considered separately.

Losses exist also in energy conversion systems (e.g., in heat exchangers, industrial heaters, pumps, and motors), the efficiency of which is limited by thermal or mechanical factors.

Of course, heat losses—i.e., the produced heat that could not be usefully utilized by the consumer and was rejected into the environment—occupy the main place in the wide spectrum of energy losses. It should be noted that more than 75% of industrial heat wastes have temperature below 800 K, due to which application of usual technologies, e.g., the Rankine steam–water cycle, for producing electricity is inefficient.

THE ORGANIC RANKINE CYCLE

There are a few basic technologies using which low-temperature waste heat can be utilized. For example, for the last 20 years energy has been generated on the basis of the organic Rankine cycle (ORC) at power stations with capacities ranging from 300 kW to 130 MW operating on different sources of heat [1, 2]. Other alternative versions are either technically impossible or economically inefficient. Leading producers of ORC-based installations have gained great experience from using low-boiling organic substances for producing electricity and have demonstrated that this cycle is well suited for low-temperature sources of heat. The ORC technology is applicable for recovering heat of medium-size gas turbines (GTs), cement plants, and geothermal sources, and yields considerable advantages as compared with the use of low-temperature steam turbines. The majority of existing systems operating at higher temperatures are fitted with a recovery unit (Fig. 1) between the heat source itself and organic working fluid (e.g., high-temperature oil). The efficiency of electricity generaton using recovered heat of industrial wastes in ORC-based systems is 12–18%; however, this parameter tends to decrease with a growth in the difference between the temperature of heat source and the maximal temperatures determined by organic fluids characteristics. Thus, in order to achieve higher efficiency, this temperature difference must be minimized by selecting the optimal temperature level for transferring heat to organic working fluid in each concrete system.

WORKING FLUIDS

The optimal working fluid must comply with the following requirements for achieving its efficient use in an ORC-based system:

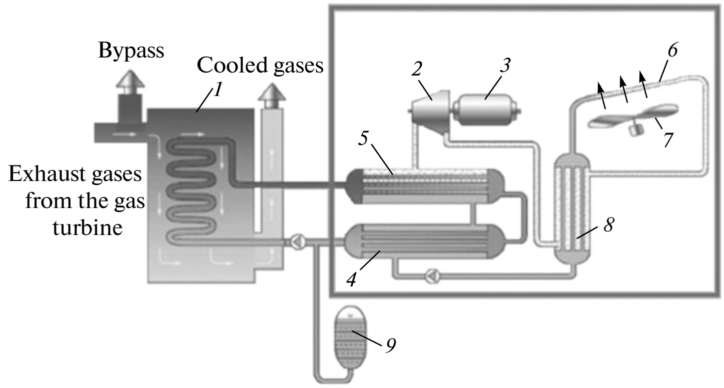

Fig. 1. Schematic diagram of the ORC-based system produced by ORMAT. (*1*) Heat recovery exchanger, (*2*) turbine, (*3*) electric generator, (*4*) economizer, (*5*) evaporator, (*6*) condenser, (*7*) fan, (*8*) recuperator, and (*9*) drain tank.

—The boundary curve in *T–s* coordinates must have a positive slope for the steam expansion process in the turbine ended in the region of superheated steam to exclude erosion of blades.

—The working fluid must have a low freezing temperature (below the cycle's lowest temperature and below the ambient temperature).

—The working fluid must have a sufficiently high temperature at which it remains stable (to avoid the occurrence of any destructive chemical reactions and decomposition).

—The working fluid must have high heat of evaporation and density for providing efficient absorption of energy from the heat source.

—The working fluid must comply with the environmental and safety requirements.

—The working fluid must be readily available in the market and have a reasonably low cost.

A preliminary analysis of different organic liquids shows that butane (R-600) is the best working fluid for implementing the ORC at a heat source temperature of 100–130°C. The use of this fluid makes it possible to obtain the highest power output from the turbine owing to low temperature of its condensation. The main drawback of butane is that it is a combustible substance. Luckily, there are a few sealing technologies, using which leaks of butane into oxidizing atmosphere are reliably prevented. Another drawback of butane (as well as other low-temperature organic liquids) is that rather high power is required for compressing it. The pumps used for this purpose are bulky, very expensive, and low-efficient.

THE CONCEPT OF THE INTEGRATED STEAM–WATER–ORGANIC RANKINE CYCLE

Various sources of waste heat, the possibilities of using it, and constraints connected with commercially available ORC-based systems were analyzed, and the integrated steam–water–organic Rankine cycle (ISORC) [3] was taken as a basis of the innovative development concept from that analysis. The main idea of this concept consists in using a back-pressure steam turbine and the ORC, in which butane serves as working fluid (Fig. 2). Exhaust gases from conventional gas turbines (GTs) or internal combustion engines (ICEs) are used in a heat-recovery boiler as a source of heat for obtaining superheated high-pressure steam, which is then supplied to a back-pressure steam turbine for generating electricity. Low-pressure steam leaving the steam turbine serves as a source of heat for generating butane vapor, which is forwarded to a butane turbine for producing additional electric energy or directly to the consumer of heat. Their ratio in systems for combined production of electricity and heat can be controlled using the butane cycle. It should also be noted that saturated vapor of low-boiling organic working fluid becomes superheated as it expands in the turbine; due to which problems connected with an increased content of moisture and ero-

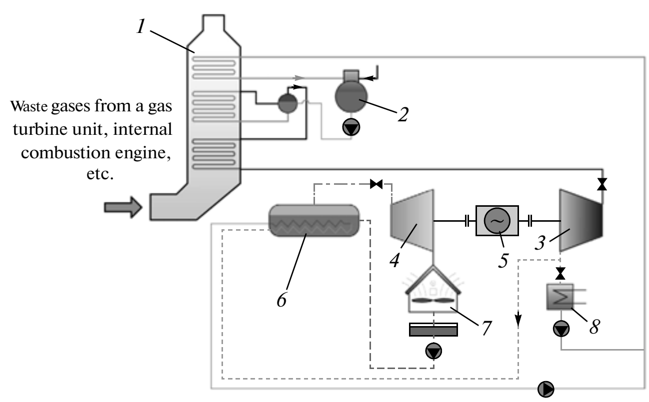

Fig. 2. Schematic diagram of the ISORC-based cogeneration installation produced by Komtek-Energoservis. (*1*) Heat-recovery boiler, (*2*) deaerator, (*3*) back-pressure steam turbine, (*4*) butane turbine, (*5*) generator, (*6*) butane vapor generator, (*7*) butane condenser, and (*8*) delivery-water heater.

sion wear of blades do not occur. One of the main features of the proposed concept is that compact and cheap jet pumps (injectors) are used for multistage butane compression instead of expensive, bulky, and inefficient pumps, due to which the losses for compressing butane will be minimized.

Losses of energy in the injectors are converted in additional heat that is also recovered in the butane cycle, whereas the use of pumps results in a lower power output of the installation. The use of butane as working fluid makes it possible to develop a compact turbine due to the fact that the volumetric velocity of butane vapor decreases in its last stages by as much as two orders of magnitude. Indeed, when steam condenses at a temperature of 30°C, its specific volume is equal to 32.9 m^3/kg at a pressure of 4.25 kPa, whereas the specific volume of butane is equal to 0.14 m^3/kg at a pressure of 0.281 MPa. Owing to this property, the butane circuit does need an intricate deaeration system. The butane turbine is very similar to a commercial gas turbine for low temperature and pressure. Such turbines are compact and reliable in operation.

ADVANTAGES OF USING THE ISORC IN HEAT RECOVERY SCHEMES

When implemented in practical applications, an ISORC-based system makes it possible to maximally utilize waste heat all the year round, whereas a back-pressure steam turbine operating in the usual cycle generates the rated electric power only for five months.

The proposed approach for utilizing waste heat has the following essential advantages over the currently used ORC-based systems:

—A higher electrical efficiency is obtained.

—It is possible to select the optimal parameters if a heat load is available.

—It is possible to control the ratio between the production of electricity and heat.

—Smaller amounts of greenhouse gases is emitted.

—The proposed system features low levels of capital investments and operating costs.

Preliminary calculations of the butane ISORC have demonstrated a 25% growth in the production of electric energy for a 6-MW commercial gas turbine and 20% growth for commercial ICEs. Gas–piston ICEs, which are widely used as drives for gas compressors and generators in natural gas distribution networks, are among possible systems in which the ISORC can be applied. For ICEs, heat losses with exhaust gases are smaller and the electrical efficiency is higher than those for gas turbines. Therefore, the increase in electrical efficiency due to implementation of ISORC is smaller for ICEs than it is for gas turbines. However, if we take into account heat losses in a cooling system of ICE, a considerably better (by a factor of 1.5) overall waste heat utilization efficiency is obtained by using the ISWORC concept.

Figure 3 shows the power performance characteristics of installations constructed on the basis of the ISORC (produced by Komtek-Energoservis) and ORC (produced by ABB). With the temperature of exhaust gases equal to 300°C, these installations have almost the same power outputs. With a higher temperature of exhaust gases, the ISORC-based installation produces considerably more energy than the ORC-based one, and the higher the temperature of exhaust gases, the greater this difference is.

For estimating the efficiency of the ISORC, we also calculated the combined system (Fig. 4) constructed using three 20V34SG gas–piston engines produced by Vartsila. The main results of this calculations are given below.

Diesel engines	
Total electric power of three machines, MW	26.2
Temperature of exhaust gases, °C	390
Thermal power of the flows of exhaust gases, MW	18.8
Full thermal power of the cooling systems, MW	12.6
Turbine	
Electric power of the back-pressure turbine, MW	1.7
Electric power of butane turbine, MW	2.3
Total electric power of the turbines, MW	4.0
Ratio of electric power obtained as a result of heat recovery to the total electric power of three machines	0.153
District heating installation	
Thermal power supplied to consumers, MW	3.8
Power performance characteristics of the entire installation	
Total electric power, MW	30.2
Overall electrical efficiency, %	53.6
Fuel heat utilization factor taking into account heat supply to consumers, %	60.4

The production of electric energy has increased by more than 15% as compared with installations without heat recovery, and the fuel heat utilization factor (determined with taking into account the heat supplied to consumers) exceeded 60%. The proposed scheme can be regarded as certain generalization of the ideas of using regeneration for making the efficiency of power-generating installations closer to the efficiency of the Carnot cycle.

Below, the advantages of using an injector are considered. Table 1 summarizes the results obtained from calculations of the main parameters for two versions of the thermal process circuit of the butane loop, which differ from one another in processes used for compressing liquid butane. With the same amount of external heat supplied in the steam generator (18 900 kW), the heating of butane is higher in the scheme without an injector than it is in the scheme with an injector.

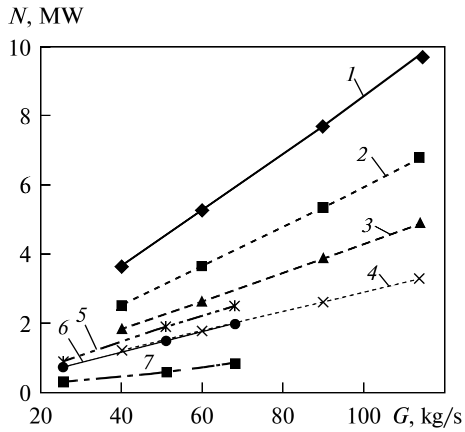

Fig. 3. Power outputs of ORC- (*1*)–(*4*) and ISORC-based (*5*)–(*7*) installations as functions of flue gas flowrate and temperature. Temperature, °C: (*1*) 466, (*2*) 400, (*3*) 350, (*4*) 300, (*5*) 350, (*6*) 300, and (*7*) 200.

Therefore, the total supply of heat in the first case must be greater.

The power required to compress butane in the scheme with an injector is by more than 200 kW smaller than it is in the scheme with single-stage compression, due to which around 7% of additional electric power output is obtained.

Preliminary assessments of the payback period of ISORC-based installations were made: assuming the specific capital investments equal to $1400 per kW of installed capacity, this period will be in the range 4–10 years depending on the cost of electric energy.

THE ORC WITH STEAM SUPERHEATING AND REGENERATION

The use of ISORC-based installations may give rise to worry on the side of consumers due to the fact that, when such an installation operates under the conditions of extremely low temperatures, emergency situation may occur if water freezes in the steam–water loop. In this case, a desire arises to do away with the steam–water circuit even at the cost of lower efficiency. The problem can be solved by using the scheme with an intermediate heat carrier (e.g., high-temperature oil) described above (see Fig. 1), due to which the heat of exhaust gases will be partially recovered. To this end, a low-boiling heat carrier with a higher boiling temperature is required (e.g., pentane or cyclopentane). The heat of exhaust gases can also be used for superheating the vapor of low-boiling heat carrier. A calculation analysis of such version was carried out as applied to a GTN-18 unit with the use of pentane (Table 2). The superheating of pentane vapor by 13.7°C made it possible to increase the net efficiency by approximately 2.4%.

Thus the innovative concept of the ISORC can be successfully implemented for achieving better thermal efficiency of industrial processes and systems of distributed generation of heat. The use of this cycle makes it possible to efficiently utilize waste heat through combined production of heat and electricity

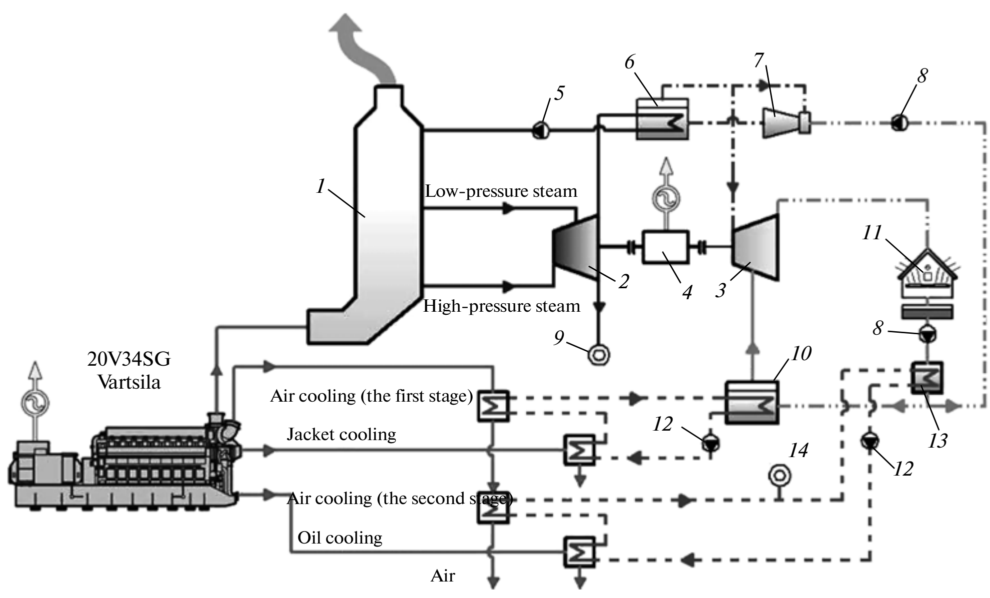

Fig. 4. Scheme of using the ISORC for diesel engines produced by Vartsila. (*1*) Steam heat-recovery boiler, (*2*) and (*3*) steam and butane turbines, (*4*) electric generator, (*5*) and (*8*) water and butane condensate pumps, (*6*) and (*10*) high-and low-pressure butane evaporators, (*7*) injector, (*9*) steam consumer, (*11*) air-cooled condenser, (*12*) circulation pump, (*13*) butane heater, and (*14*) district heating.

Table 1. Parameters of the butane circuit

Parameter	System	
	with an injector	without an injector
Heat supplied in the steam generator from heating steam, kW	18900	18900
Butane vapor for the injector:		
injection ratio	3.41	–
enthalpy, kJ/kg	746.4	–
pressure, MPa	2.63	–
flowrate, t/h	42.1	–
Vapor downstream of the butane turbine		
flowrate, t/h	143.7	145.3
pressure, MPa	0.2814	0.2814
enthalpy, kJ/kg	674.5	674.5
Liquid butane in the injector		
pressure at the inlet/outlet, MPa	0.8/2.9	–
temperature at the inlet/outlet, °C	30.5/72.5	–
enthalpy at the inlet/outlet, kJ/kg	272.8/380.2	–
flowrate at the outlet, t/h	185.8	–
Liquid butane in the pump		
pressure at the inlet/outlet, MPa	0.2814/0.8	0.2814/0.8
temperature at the inlet/outlet, °C	30.0/30.5	30.0/32.3
enthalpy at the inlet/outlet, kJ/kg	271.5/272.8	271.5/278.1
specific work of compression, kJ/kg	1.3	6.6
specific volume, m^3/kg	0.00176	0.00176
flowrate at the outlet, t/h	143.7	145.3
Condensate pump:		
efficiency, %	70	70
consumed power, kW	52	266
Net turbine internal power, kW	2818	2636
Thermal efficiency of the cycle, %	15.0	13.9

Table 2. Effectiveness of pentane superheating

Parameter	System	
	with saturated vapor	with superheated vapor and regeneration
Pentane vapor temperature at the turbine inlet, °C	180.2	193.9
Pentane vapor pressure at the turbine inlet, MPa	26.2	24.3
Pentane vapor condensation temperature, °C	40	40
Net electric power of the installation, kW	4155	4816
Net electrical efficiency of the installation, %	14.0	16.4

by means of a back-pressure steam turbine and the butane ORC.

The proposed concept can be applied both in developing new installations and in retrofitting existing ones. In the latter case, more than by 20% higher production of electric energy is expected. The overall electrical efficiency of the system with combined production of heat and electricity can be increased to 58–60%.

In addition, the energy efficiency achieved in the case of using the ISORC is higher than that of the existing ORC-based systems. Since the yield obtained from using the ISORC at the waste heat temperature equal to around 300°C is close to that from using the ORC, the ISORC can be regarded as an economically efficient alternative at flue gas temperatures in the range 300–500°C.

REFERENCES

1. L. Y. Bronicki, *Organic Rankine Cycle Power Plant for Waste Heat Recovery* (ORMAT, 2005), www.ormat.com.
2. *Energy Use and Opportunities Analysis: US Manufacturing and Mining* (US Department of Energy Industrial Technologies Program, 2004).
3. Y. Chudnovsky, M. Gotovsky, M. Greenman, et al., "Steam Organic Rankine Cycle (SORC) for Distributed Generation and Combined Heat and Power Production," in *Proceedings of IHTC-14 (IHTC14-22704), Washington, 2010.*